Renewable and Sustainable Energy Reviews 15 (2011) 236–251

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Modern power-electronics installations in the Polish electrical power network

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ARTICLE INFO

Article history:
Received 11 May 2010
Accepted 9 September 2010

Keywords:
Power network
FACTS
Wind installations
Energy storage
Fuel cell

ABSTRACT

The paper discusses the most important areas of application of power electronics arrangements in the Polish electrical power system; especially in the distribution system. The examples presented demonstrate both the need for and the purpose of further research and its applications in these fields, as well as indicating the direction of future research, with special consideration given to the research required in Poland. The proposed practical solutions for power electronics arrangements, either dedicated or capable of adaptation to the distribution systems, illustrate the ability to use the potential of Polish national research-development units.

Contents

1. Introduction

While, according to prognoses, the use of electrical energy (EE) is rising, the level of investment in the Polish electrical power network (EPN) is in the best case stagnant. In Poland traditional solutions are still preferred in the form of new power stations and grid lines and associated equipment, in spite of the fact, that the process of their localization and construction is difficult, expensive and time-consuming. The eventual investments are as a rule carried out on the basis of a compromise between cost and the required reliability of the electrical energy supplied, which favors a change in the power lines from opened to closed. Unfortunately, such a change leads equally to a reduced power flow control capability. This is particularly risky in the case of the loss of one line, causing an overloading of others and increasing the probability of a blackout. Moreover, a massive increase in the loading leads to a "bottleneck" on key lines and, consequently, to an ineffective functioning of the energy market. A solution would seem to be a reshaping of the present EPN into a so-called "intelligent" electrical power network (IEPN), one of which

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doi:10.1016/j.rser.2010.09.015

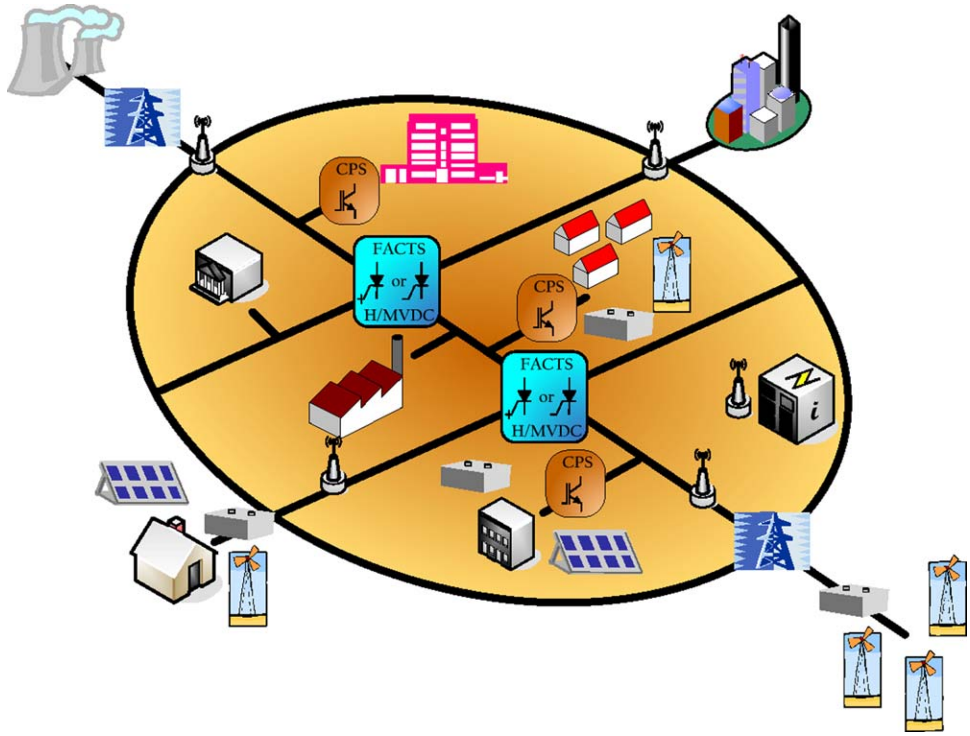

Fig. 1. Conception of "intelligent" power network.

conceptions is presented in Fig. 1. This boasts equally complete controllability as well as flexibility and reliability. Moreover, an IEPN enables the creation of self-regulating platforms for the integration of a large number of distributed sources and main power stations [1,2].

One of the basic conditions of transforming a traditional EPN in an IEPN is the wide-spread use in electrical power networks of modern power-electronic installations (PI), in which there are installations of the type FACTS (Flexible AC Transmission System) and HVDC (High Voltage DC) [3–5], either M(Medium)VDC or L(Low)VDC, as well as a great many installations of the type CPS (Custom Power Supply) [6].

Wide-spread use of PI is recommended also in modernized traditional EPN. For example switch-gear equipment used up to the present is in the majority of cases mechanical devices. Their speed of operation is satisfactory for the control of EPN in given situations, but is inadequate in situations demanding reactions to unexpected changes in voltage and flow conditions. This negative feature of mechanical devices is particularly demonstrable in response to ever increasing demands in the area of quality of electrical energy [7–9]. A wider application of PI in EPN today would allow for a fuller exploitation of existing distribution and transmission resources, while maintaining the status so far, and even improving the safety of the power supply and energy efficiency.

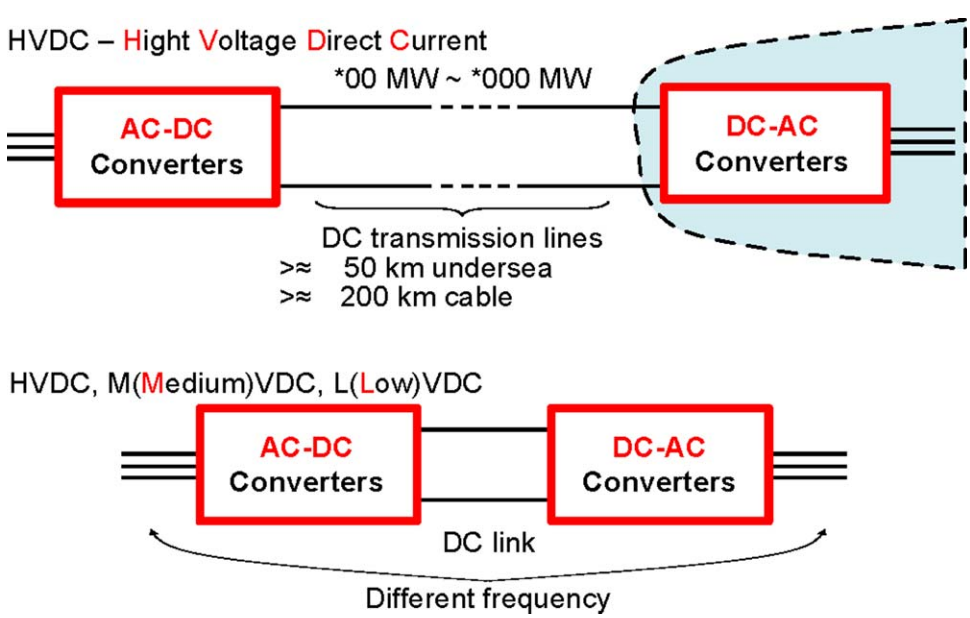

Fig. 2. Power-electronics in DC transmission systems.

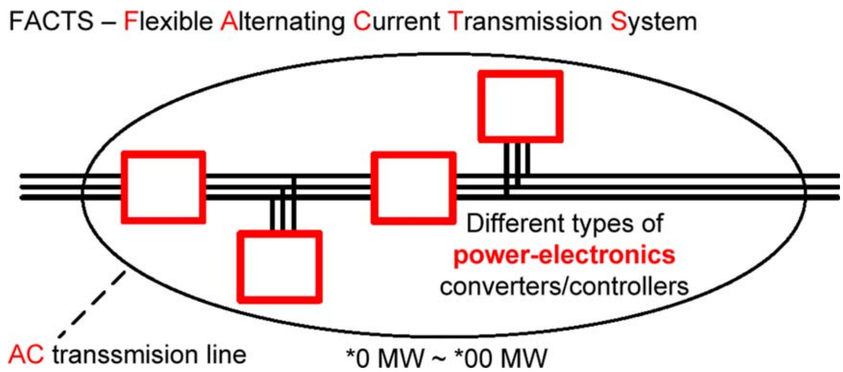

Fig. 3. Power-electronics in AC transmission systems.

The general aim of this article is to present the areas and the possibilities for implementing modern power-electronic installations in the Polish EPN, with particular reference to distribution systems with a large participation of distributed sources, in particularly renewables. An additional aim is to present selected practical solutions based on the research of the authors, illustrating some Polish scientific and technical possibilities.

2. The use of power-electronics in power network

The area of application of PI in EPNs can be generally divided into: (a) electrical energy transmission system, (b) electrical energy distribution system. The transmission system is composed basically of two complementary technologies for controlling the transmission of energy [5]: (a) with conversion to DC current – HVDC devices; (b) directly – FACTS devices. A general comparison of these devices is illustrated in Figs. 2 and 3.

An advantage of HVDC devices is the capability to transmit energy between systems of various frequencies. However, in the case of conventional HVDC, i.e., with the use of SCR thyristors, it is necessary to use large filters and there is no possibility of supplying power to end-users on the side from which the source is disconnected. This drawback does not occur when using modern devices, such as GTO thyristors or IGBT transistors [30]. Here, one should note that with HVDC devices the entire energy from one system flows into the other through converters. As a result of this the cost is high, even in single-station installations. While in FACTS devices, such as:

- SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator),
- TCSC (Thyristor Controlled Series Compensator), TSSC (Thyristor Switched Series Compensator) and SSSC (Static Synchronous Series Compensator),
- SPS (Static Phase Shifter),

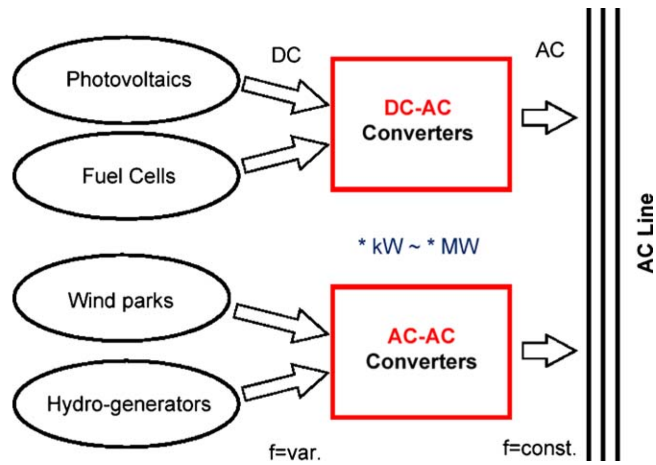

Fig. 4. Power-electronics in alternative generation systems.

- UPFC (Unified Power Flow Controller),

only part of the power flows through the power converter. Such devices can be applied, however, to the control of EE flow only in AC systems with a single frequency.

A decidedly greater variety of PI occurs in distribution systems. In these systems power-electronics converters/controllers are applied in general to:

- matching parameters and coupling of distributed sources with power lines or local end-users, and controlling consumption of EE with these sources (Fig. 4),
- matching parameters and coupling of energy storage with power lines, and controlling the exchange of energy between storage systems and power lines (Fig. 5),
- improving the quality of the power supply, among other things: compensation of sags and swells, asymmetry and distortions of

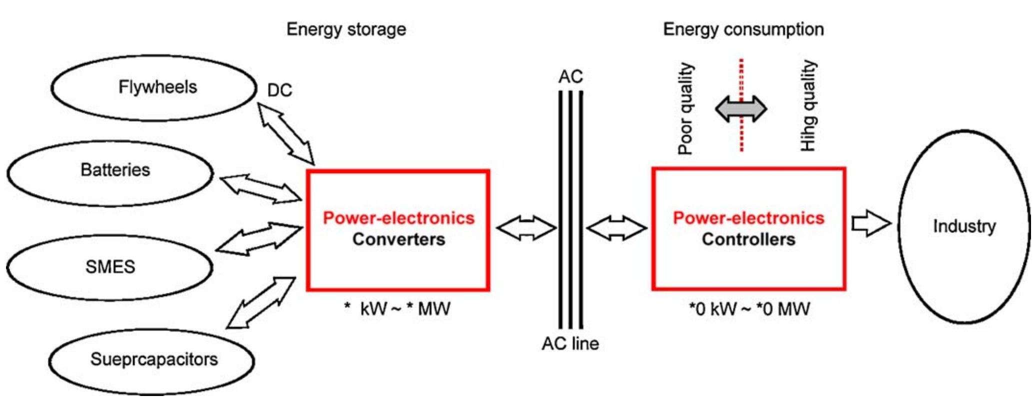

Fig. 5. Power-electronics in storage systems.

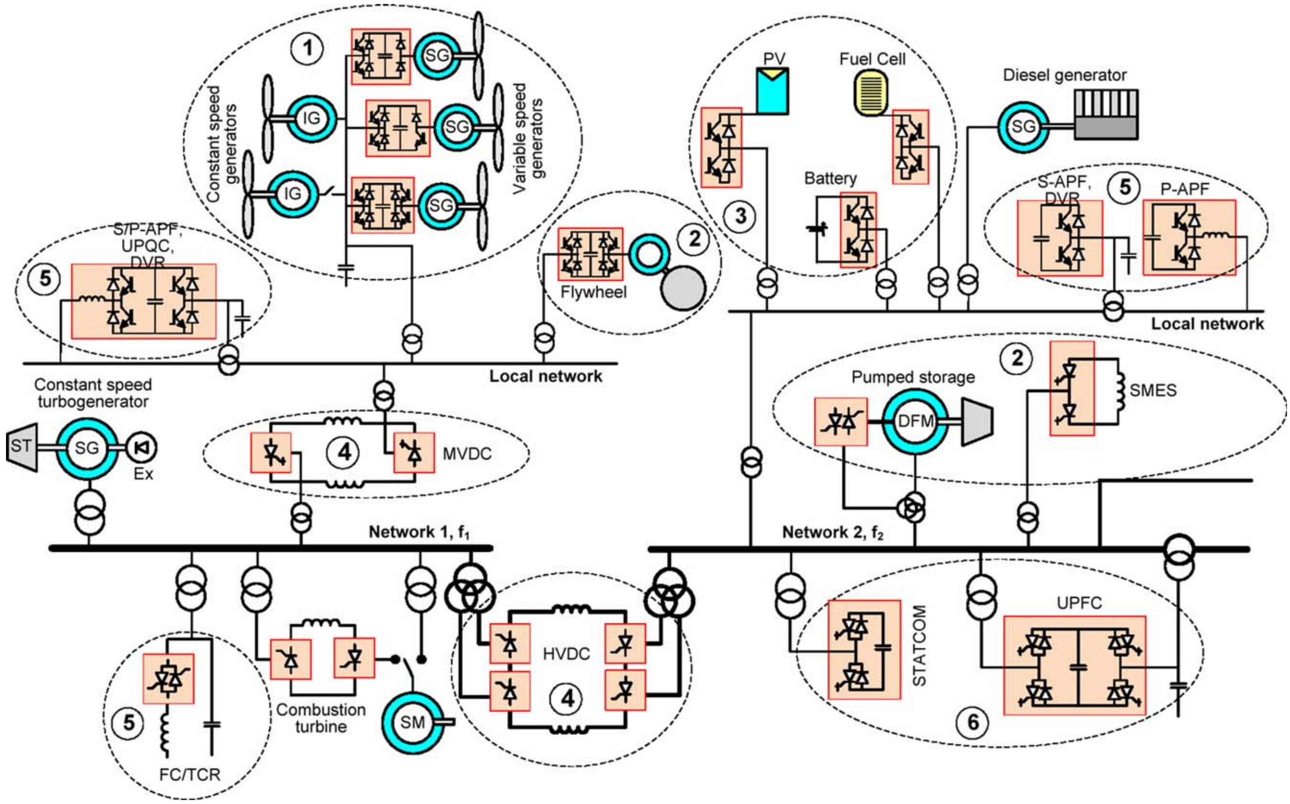

Fig. 6. Area of application of PI in EPN: 1 – wind generators, 2 – energy storage, 3 – power supply systems from low-voltage sources, 4 – network couplers, 5 – devices for improvement of energy quality, 6 – devices for control of energy delivery.

supply voltage, as well as compensation for distortion, asymmetry and phase shift in load current (Fig. 5).

3. Examples of applications of PI in power network

Fig. 6 illustrates the most important areas of use of PI in EPN, at various levels of power. Further discussion of these areas, with reference to objects of this paper and common characteristics of applied solutions, are limited to:

- wind installations,
- energy storage and of low-voltage sources,
- network couplers and installations improving energy quality.

3.1. Wind installations

The most frequent area of application of PI in wind installations is in generators (Fig. 7) [10,11]. In the beginning the most commonly applied device was the squirrel cage induction machine (IM) connected directly to an EPN, and power-electronics used solely in a simple connection-starting device. As a result, in such installations there occurs a transfer of the pulsation of the wind power to the power network and, moreover, there is no means of direct control of the active and passive power. The significance of such control, desirable for the control of voltage and frequency in an EPN, increases along with the rise in power [10,12]. As a result of this, generators with squirrel cage induction machines connected directly to an EPN are sporadically applied to new installations of large power. Rarely installed too, on account of power losses and limited means of regulation, are generators with wound rotor induction machines (WRIM) and power-electronic adjustable resistance in the rotor circuit [13].

Currently in Poland 70–80% of turbines uses are:

(a) double feed wound rotor induction machines (DFIM) with an AC–DC/DC–AC converter in the rotor circuit,
(b) synchronous machines (SM) with an AC–DC/DC–AC converter in the main line and an AC–DC/DC–AC converter in the exciter circuit,
(c) permanent magnet synchronous machine (PMSM) and AC–DC/DC–AC converter in main line.

There are also generators with squirrel cage induction machines (IM) but with self-excitation and an AC–DC/DC–AC converter in the main line (designed for full power) [13–15]. All these solutions, although more costly than the ones applied at the beginning of the development of wind power in Poland, are characterized by much better regulatory qualities, among which are: the capability of adjusting active and passive power; the capability of operating at varying shaft rotation speeds, rapid reaction to change of wind conditions (0.5–1 ms); avoiding influence and resistance to deteriorating quality of EE in an EPN; and the capability to work in islanding mode [10,12]. These aspects support the implementation of the vector control method applied originally to the motor drives [16–18], as well as the MPPT (Maximum Power Point Tracking) algorithms enabling full use of the available wind energy [14]. Multipolar SM and PMSM permit through this the elimination of a mechanical transmission system, which raises the reliability of the turbine.

Heavy duty power-electronic converters are equally employed on wind farms, taking care of at least a few connected turbines situated close by. The configuration of farms is equally dependent on the kind of generator as well as the type of converter used and the topology of the EPN [10–12]. A typical example is the connection of turbines with generators, shown in Fig. 8.

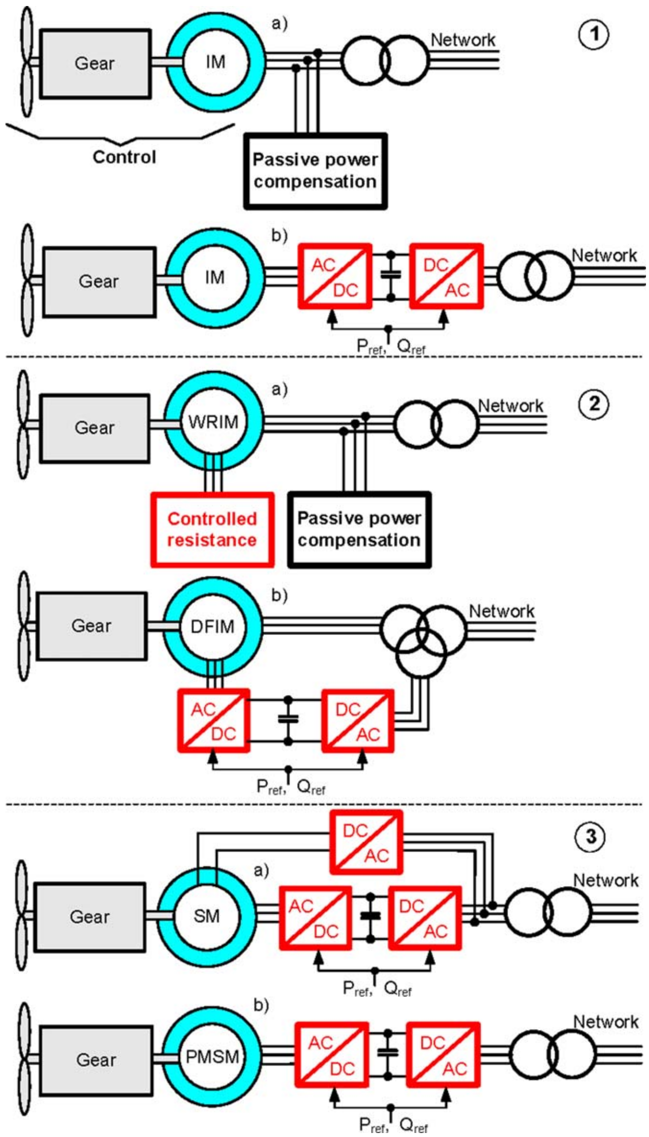

Fig. 7. Basic types of wind turbine generators.

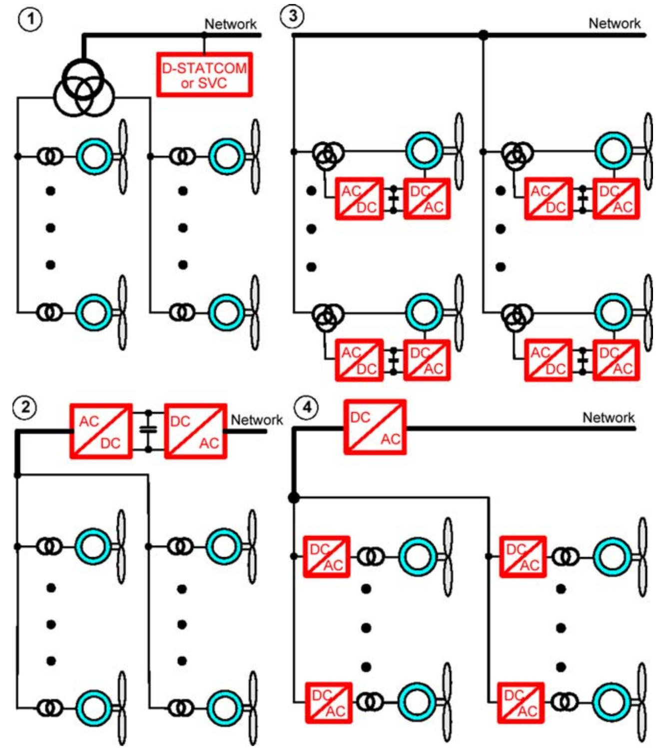

Fig. 8. Typical connection of turbines with induction machines used on wind farms: (1) with passive power compensator (D-STATCOM or SVC), (2) with common DC link to the power network, (3) with internal DC network and individual control of power, (4) with individual control of power.

On a farm as shown in Fig. 8(1), having groups of turbines with squirrel cage induction machines, the D-STATCOM (or SVC) supplies passive power to the machine and assists in maintaining the voltage profile in the network. Unfortunately this farm does not lend itself to individual control of the turbine power or control of the circulating power between turbines. It is equally impossible to eliminate the phenomenon of wind power pulses from the network. The latter drawback is, however, removed from the farm presented in Fig. 8(2), since the DC link (AC–DC/DC–AC converter) allows the control of not only passive power and network voltage profile, but also the direct control of active power supplied to the network. This solution creates also the interesting option of connecting a farm located at a distance from the existing EPN with the DC line.

An extended concept for use of DC couplers on wind farms is illustrated in the configuration presented in Fig. 8(3). The rectifier part of the heavy duty AC–DC/DC–AC converter (Fig. 8(2)) is divided into particular turbines, forming in this way an internal DC network, as well as enabling individual control of turbine power. In this respect it is noteworthy that matching turbines to a DC network is significantly easier than to an AC network, because the DC network requires only one control parameter (amplitude), while the AC network requires as many as three (amplitude, frequency and phase). Moreover, dividing a DC network simplifies the connection of energy storage devices. For this reason AC–DC/DC–AC converters are used on farms, in general, only in such cases where they have already been integrated into the turbine by the manufacturer. Most often this concerns turbines in which there are generators with DFIM machines (Fig. 8(4)) or PMSM. AC–DC/DC–AC converters for individual turbines can be equally justified in cases of very high power.

3.2. Energy storage and low-voltage source systems

Energy storage, in the form of batteries, is widely used in back-up power supplies. In such devices flywheels exploit greater power [18], amassing kinetic energy. An example of a kinetic resource, constructed in the form of a container, is shown in Fig. 9. Quite

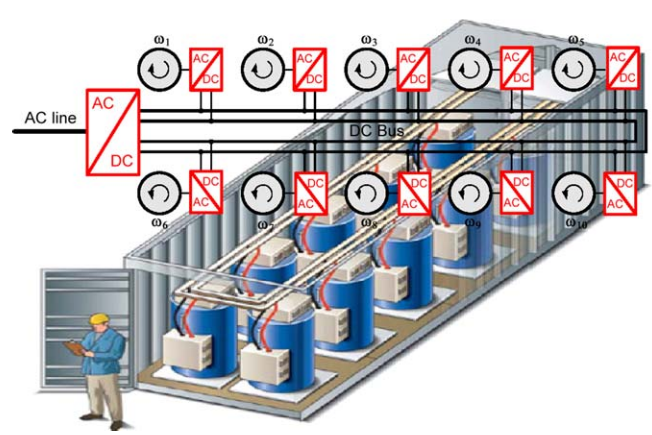

Fig. 9. Example of a kinetic storage container.

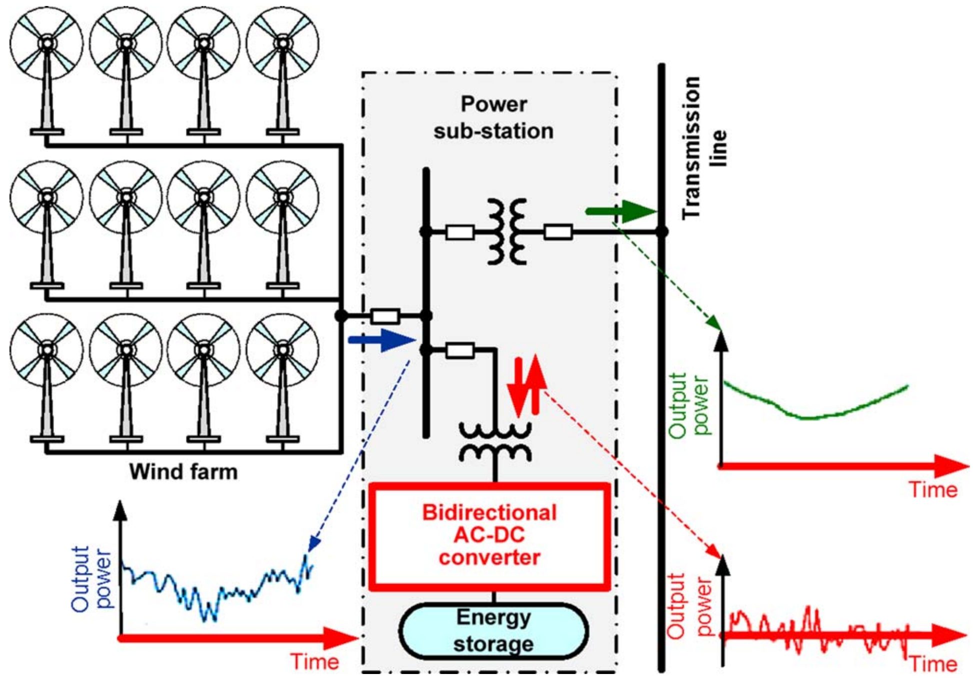

Fig. 10. Implementation of energy storage for the compensation of active power pulsations on output of wind farms.

small fast-rotating kinetic storage resources are connected to an internal DC bus through an AC–DC converter, and only then through a DC–AC converter to an AC line. It should be emphasized that the greatest difficulty in constructing a modern kinetic storage is tied not to power-electronics, but to high-speed flywheel rotation technology (60,000–90,000 RPM).

Batteries, flywheels and other storage, such as: water containers, hydrogen systems, heat energy storage, supercapacitors, superconductive storage or compressed air tanks are also used in distributed sources [2,20]. The goal is the improvement of the availability of these sources, i.e., the amelioration, or even elimination of the influence of external conditions (weather) on the power temporarily supplied to the EPN. For the connection of such resources to the network various PI are employed.

Fig. 10 illustrates an example of the exploitation of an energy storage unit for the compensation of active power pulsations caused by the fluctuations of the wind energy. The degree of compensation depends on the size and dynamic qualities of the energy storage as well as the control algorithm used [21]. This in turn has an influence on the power of the converter, the type of which is chosen with respect to bidirectional energy flow and kind of energy storage. For example, for batteries it will be an AC–DC converter, and for a flywheel with an AC motor, an AC–AC converter. The power of the converter depends, too, on its additional functions, e.g., its passive power compensation efficiency.

In the case of the exploitation of energy storage and low-voltage sources, the configuration of the source and the means of matching the voltage levels have a decisive influence on the qualities of the chosen solution. Typical examples here would be a power supply with a photovoltaic cell (PV) and a fuel cell (FC) [22–24], in spite of the fact that such cells, in contrast to energy storage, do not have the capability for bidirectional energy flow.

PV systems are differentiated by three basic connection configurations, illustrated in Fig. 11. The most universal, though

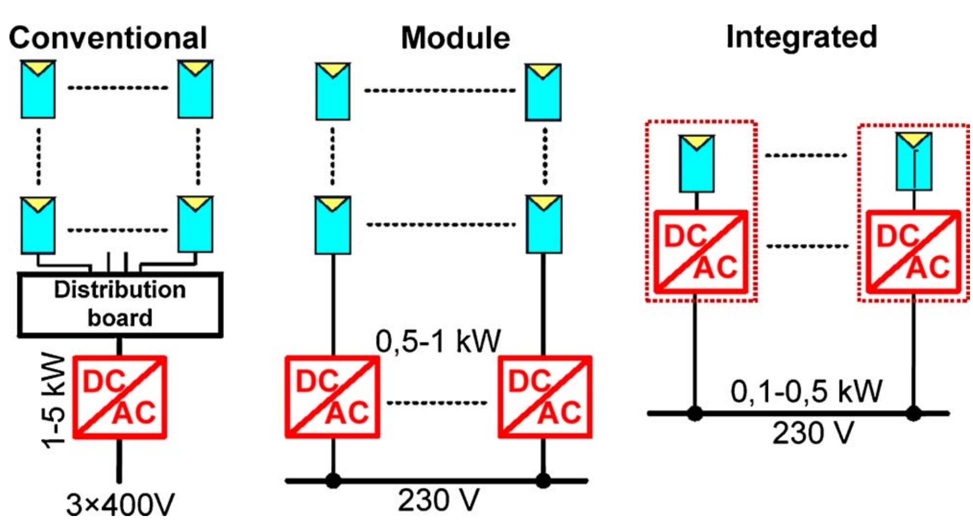

Fig. 11. Typical configurations of power supply systems with PV cells.

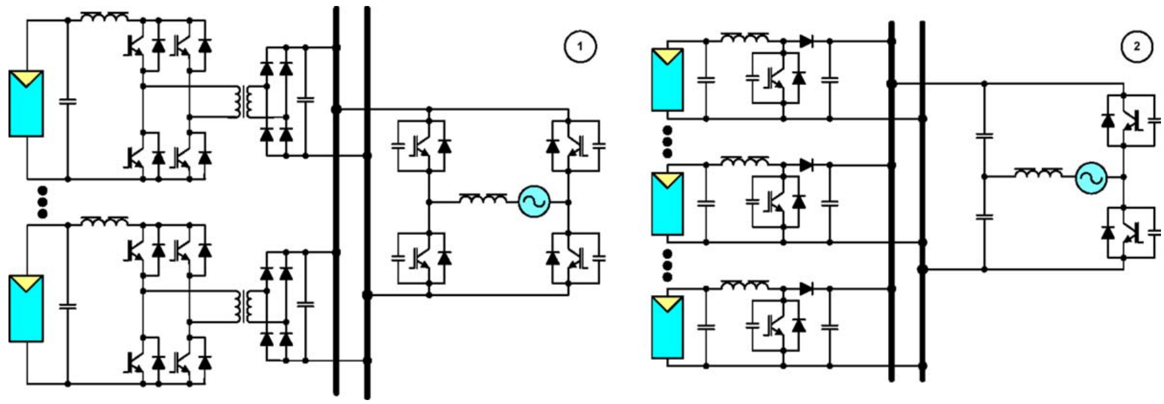

Fig. 12. Example connections of PV cells to distribution networks.

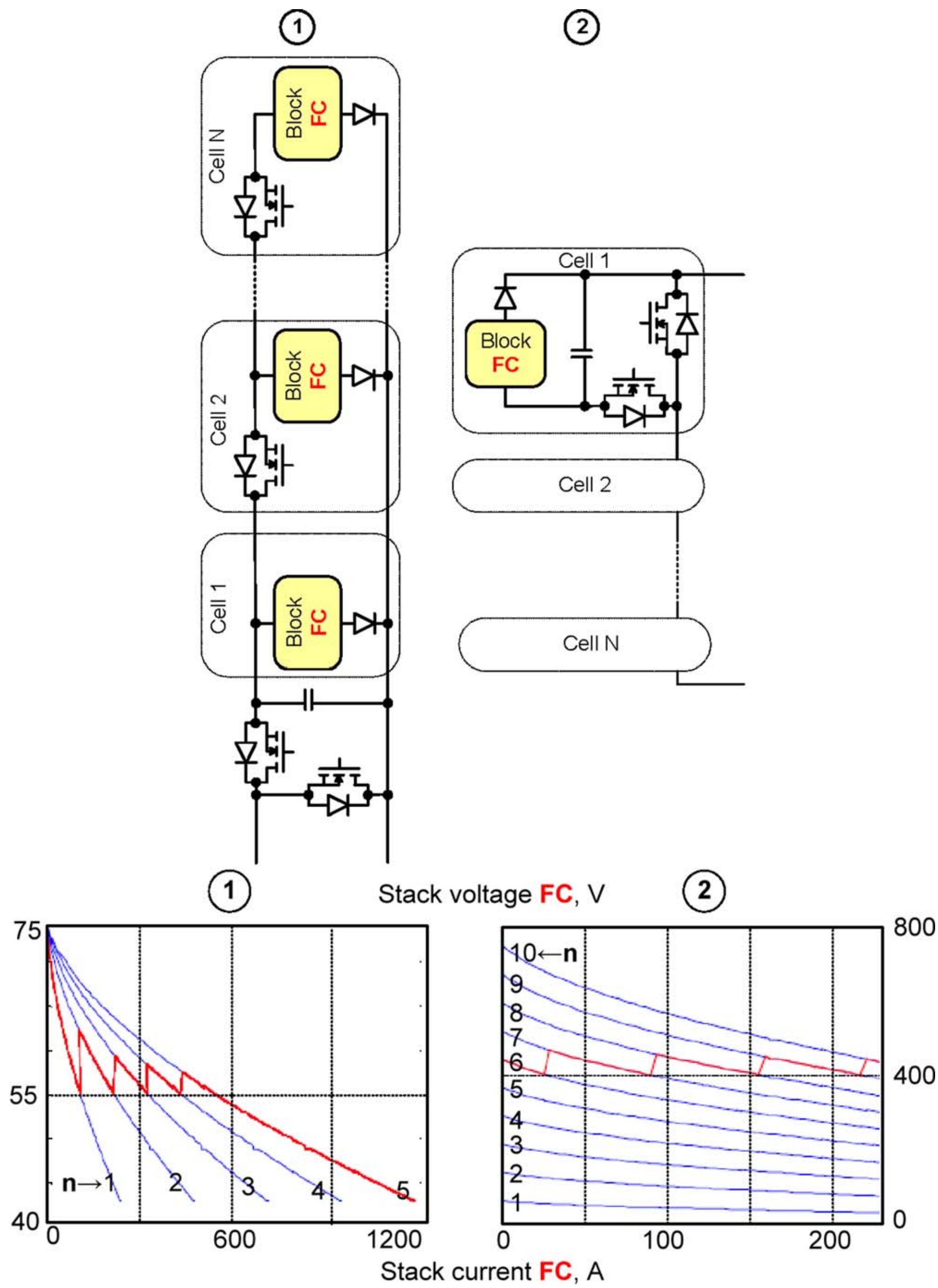

Fig. 13. Parallel and series connection of FC in stacks and their characteristics.

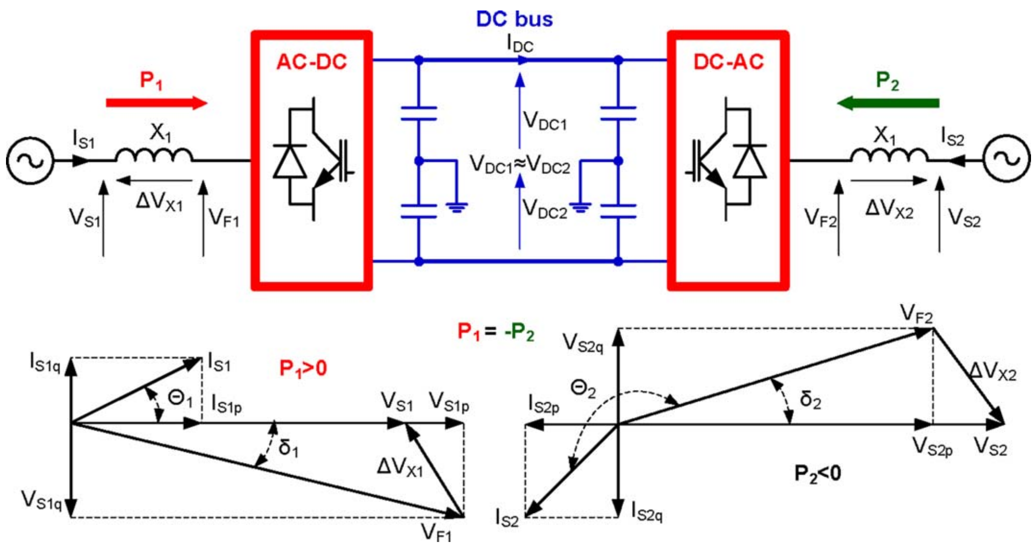

Fig. 14. Structure and working principle of "back-to-back" network coupler with intermediate direct current bus.

at the same time the most demanding in respect to the PI, is a configuration with a modestly sized DC–AC converter integrated into the PV module. The converter should be characterized by: very high efficiency and minimal size, increased voltage cell and sinusoidal output voltage as well as the ability to work with parallel connections. These requirements enable the connection to various PI with impulse modulation, e.g., [22,23,25–29], realized on the basis of currently available power-electronic components [30–33].

In conventionally configured PV systems, generally of greater power, an internal DC bus is frequently used (Fig. 12). Its purpose is similar to that of the case of the wind farm illustrated in Fig. 8(3). A DC bus also permits easier galvanic isolation of the PV cell with the help of high frequency transformers (Fig. 12(2)), and in addition, may be an integrated part of the internal direct current micro-network [34–37].

In a similar way to the PV system, with the use of a geminate PI and DC bus, systems with FC elements are likewise configured [24,38]. In this case, taking into consideration the soft output characteristics and low voltage of individual cells, the connection of fuel cells in the stack is of decisive significance to the required output voltage and load capabilities. Fig. 13 illustrates example configurations of fuel cell connections in series and parallel stacks as well as current–voltage characteristics of these stacks.

3.3. Network couplers and energy quality improvement devices

Power-electronic network couplers and energy quality improvement devices have many common features with energy delivery control devices. A basic difference is in the function and location of these devices in the EPN [6].

The most universal couplers are "back-to-back" type devices, composed of two fully controlled AC–DC and DC–AC converters (voltage or current), connected by a DC bus [39–42]. While one converter works as an inverter the second acts as a rectifier. A change in the working mode of the converter causes a change in the direction of the power flow. In so doing, always only active power will flow through the DC bus, which acts as an insensitive device to frequency and phase differences in a coupled network. Furthermore, in respect of the DC bus each converter may equally independently fulfill additional functions as an EE quality improvement device, and, in the case of connecting energy storage, as a source of "interventional" power [6,8,9,40,43]. The basic function of a "back-to-back" coupler, where voltage converters are

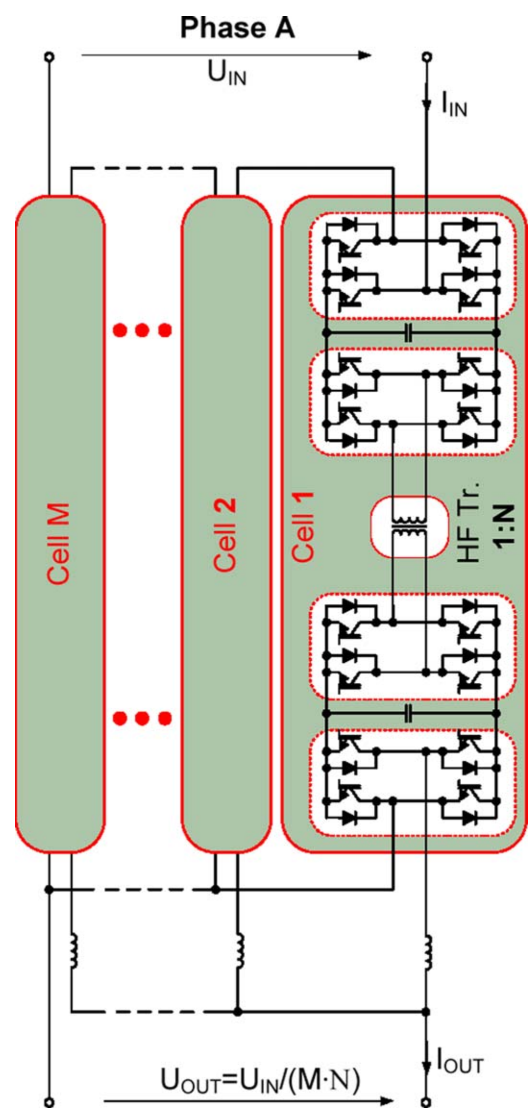

Fig. 15. Integrated distribution transformer.

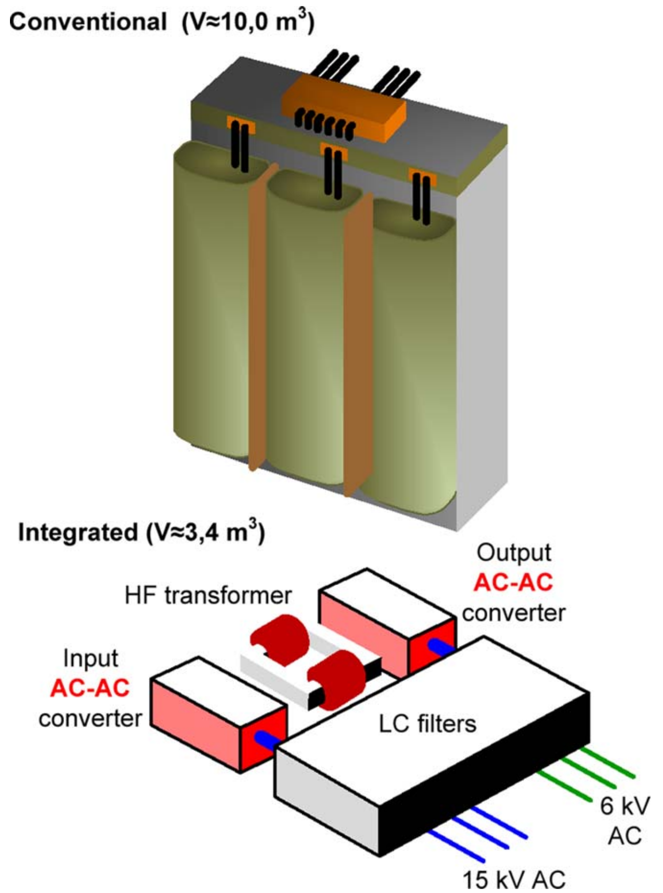

Fig. 16. Construction and comparison of conventional and integrated transformer body dimensions.

used, is clarified by the explanatory curves shown in Fig. 14 and the dependencies (1)–(5).

$$P_1 = V_{F1} \cdot V_{S1} \cdot \frac{\sin \delta_1}{X_1} \tag{1}$$

$$Q_1 = \frac{V_{F1} \cdot V_{S1}}{X_1} \cdot \cos \delta_1 - \frac{V_{F1}^2}{X_1} \tag{2}$$

$$P_2 = V_{F2} \cdot V_{S2} \cdot \frac{\sin \delta_2}{X_2} \tag{3}$$

$$Q_2 = \frac{V_{F2} \cdot V_{S2}}{X_2} \cdot \cos \delta_2 - \frac{V_{F2}^2}{X_2} \tag{4}$$

$$P_1 = P_{DC} = V_{DC1} \cdot I_{DC} = V_{DC2} \cdot I_{DC} = -P_2 \tag{5}$$

In practice "back-to-back" devices are connected to networks by transformers [44–46]. Such connections serve, above all, to match the voltage in the AC–DC/DC–AC converters and in the network couplers. Employing transformers is also recommended in voltage matched "back-to-back" devices, e.g., when using multi-level converters [47,48]. In this case, thanks to galvanic separation, the operational safety is increased and malfunctions are ameliorated. Moreover, transformers in parallel "back-to-back" devices enable improvement of the voltage form at the coupler's terminals [46,49].

Because network transformers increase in a significant way the size of coupling installations, there has been quite recently development of new coupling devices with galvanic separation, aided by DC–DC converters with a high-frequency transformer [50]. The idea of such devices, known also as integrated distribution transformers [51], is illustrated in the scheme shown in Fig. 15. Each phase consists of M identical AC–DC–AC–Tr–AC–DC–AC converter cells, series connected on the side of the higher voltage, and in parallel, on the side of the lower. Possible are other cell connections, by which it is always necessary to ensure equal loading and equal voltages. It is estimated that high power and medium voltage integrated distribution transformers, ensuring the same functional capabilities as typical "back-to-back" couplers, will be about one-third the size of conventional transformers (Fig. 16).

Modern PIs serving to couple AC and DC networks as well as to match distributed sources and energy storage already today enable the building of local micro-networks as a part of an IEPN [2,34–37,52]. For example, if we consider the micro-network structure shown in Fig. 17, we gain a highly flexible integration of distributed sources and the capability of "plug-and-play" type

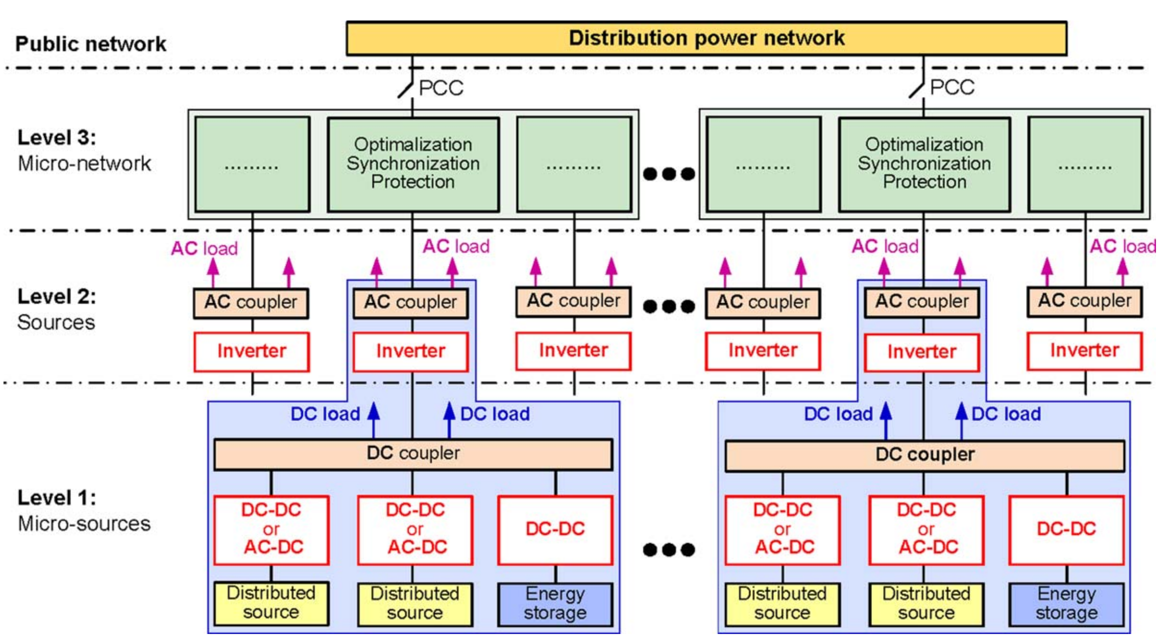

Fig. 17. Hierarchical structure of hybrid micro-networks with DC and AC couplers.

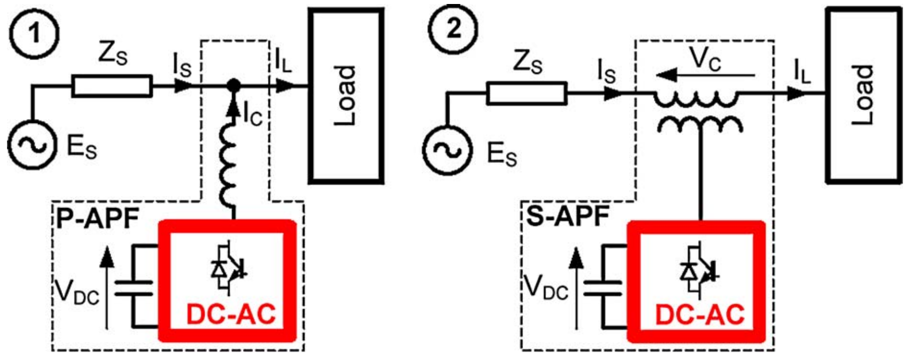

Fig. 18. Basic APF schemes: (1) parallel, (2) series.

functions at every level, without the necessity of implementing non-standard solutions. Here it is understood that the most effective working conditions of the power network (with a micro-network in it) occur in the case of steady loads with a power coefficient of $\lambda \approx 1$ [8].

With the aim of improving the coefficient $\lambda < 1$, on the output or directly on the input (load), various compensatory-filter devices are installed. Among the implemented solutions [8,53], the most universal are active power filters (APF) [8,9,19,41,42,53,54]. APF devices, depending on the control algorithm, enable a connection

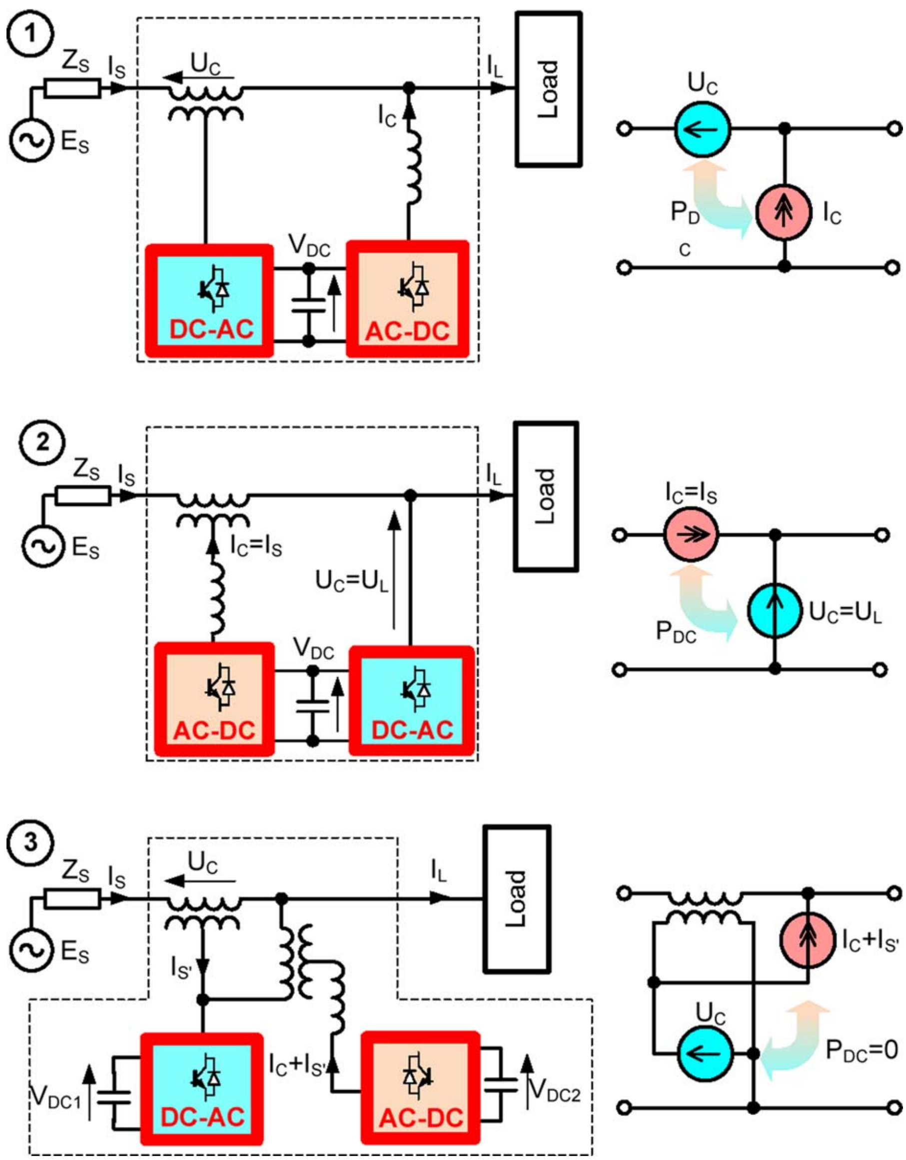

Fig. 19. Series-parallel APF devices: (1) compensatory, (2) forced, (3) without common DC bus.

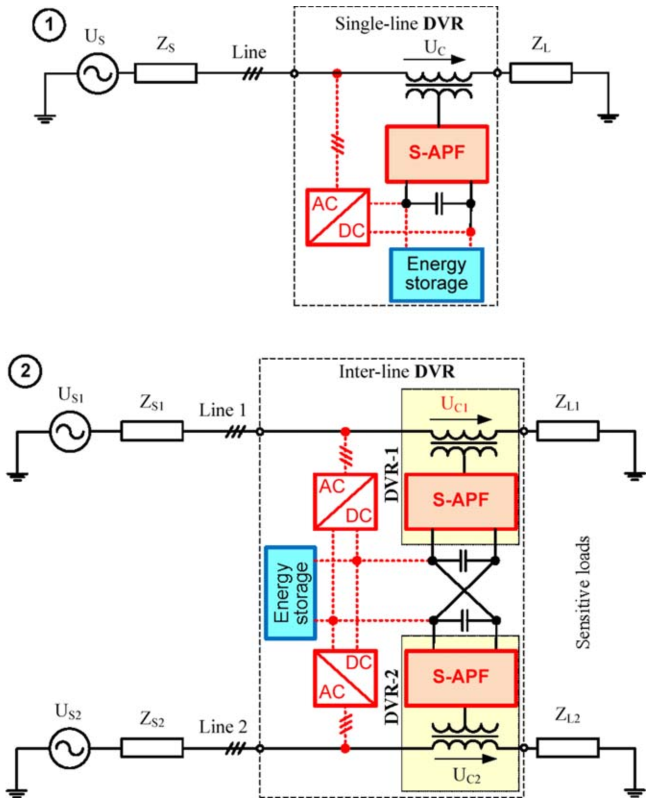

Fig. 20. Example DVR devices: (1) single-line, (2) inter-line.

or selective compensation of all undesirable current components and/or voltage.

Fig. 18 illustrates two basic APF devices: parallel (P-APF/ Parallel-APF) and series (S-APF/Series-APF). The P-APF device (Fig. 18(1)) is primarily intended for current compensation, and the S-APF device (Fig. 18(2)), for voltage compensation. Sometimes the S-AFP device is also used to force a desirable current, and the P-APF device to force a desirable voltage. The choice of APF device and its use depends on the character of the load and the network, as well as on the demands concerning EE quality [54].

In some cases, in order to achieve the required quality of EE, it is necessary to use series-parallel APF devices (Fig. 19). These devices, also called UPQC (Unified Power Quality Conditioner) [54–57], are in general constructed as integrated P-APF and S-APF connections with a common DC bus. The device in Fig. 19(3) does not have a common DC bus [58], which enables the application of multi-level DC–AC and AC–DC cascade converters [47,48].

Dynamic voltage restoration devices (DVR – Dynamic Voltage Restorer) are a certain kind of active filter, somewhere between S-APF and UPQC [6,9,59–62]. Fig. 20 illustrates their general construction and location in the distribution system. When there is a voltage disturbance in the power supply, the DVR device immediately restores the correct voltage, ensuring the proper power supply to sensitive loads, with the exception of situations where there is an interruption in the power supply or frequency deviation. Specifically, DVR enables compensation for voltage sags.

Due to the demands of generating or receiving active power over a relatively long period of time (even a few seconds), the DVR device (in contrast with an S-APF) is equipped with additional energy storage connected to the DC bus. Sometimes, with the aim of reducing energy storage or in situations where prolonged disturbances occur, parallel AC–AC converters are used, in a similar manner to a UPQC. There is a difference in the type of converter, which for a DVR can be a diode rectifier. Naturally it is the case here that the UPQC device may also function as a DVR, but such a solution is unnecessary and uneconomical. A smaller energy storage is likewise necessary in inter-line DVR devices (Fig. 20(2)), which results from the possibility of exchanging active power between power lines.

4. Authors' prototype solutions

There is a global tendency of increasing participation of modern PI in EPN, the goals of which are generally tied to:

- optimal exploitation of existing power network infrastructure, and thereby:
  - improving the safety of supply and ensuring the highest possible quality of EE,
  - reducing EE losses and making better use of installed power,
  - economizing on mined energy resources,
  - reducing the number of large energy investments;
- technical security of the EE free-market;
- securing power supplies to new sensitive technologies and with new challenges in the areas of:
  - development and dissemination of renewable sources of EE,
  - transformation of an existing EPN into an "intelligent" EPN.

With this tendency in mind, in Poland over the last few years there has been engagement in scientific-developmental and initiative work, part of which results are presented below as prototype solutions. These solutions, researched by the authors, arose mainly with the idea of application in power systems.

4.1. A 4-level 6 kV/1 MVA inverter

A prototype inverter, whose scheme and internal details as well as typical output current and voltage waveforms are presented in Fig. 21, was built within the framework of a developmental project. The device employed IGBT transistors of the type FD200R65kF1-k and FZ200R65kF and Concept controllers triggered through optical fibers. The control algorithm, implemented in the DSP programmer, comprises vector modulation and safety functions as well as communication with a commercial computer [63]. From the computer there are assigned superordinate control parameters, among which is the operational mode. The inverter was designed in such a way as to enable its use as a D-STATCOM (after adding common mode chokes), as well as in motor drives. Taking into account technical limitations at the research station, an experiment with a voltage of 6 kV was conducted with a motor drive only. The results achieved from the research, confirming the anticipated outcomes, are illustrated in the oscillogram in Fig. 22.

4.2. Quasi-Z inverter for a low-voltage source

The initial laboratory prototype of the quasi-Z inverter (Fig. 23) was constructed on the basis of research by Prof. Peng [64] and the authors' own [29,65]. The inverter is designated for use with quite small (1–3 kW) 3-phase loads supplied from a low-voltage DC source, in particularly from a photovoltaic cell. Its advantages are a one-stage energy conversion and relatively high DC voltage rise coefficient, as well as, in comparison with earlier-known type Z devices, uninterrupted input current. In experiments to-date a rise in voltage from 40 V DC to 180 V AC has been achieved. Registered patents of new modifications, among which are the type T device [65] and the quasi-Z cascade device, should make possible an achievement of 400 V DC, which fact has been confirmed in a detailed simulation. The developed prototype has received attention from one Polish company working in the field of power systems.

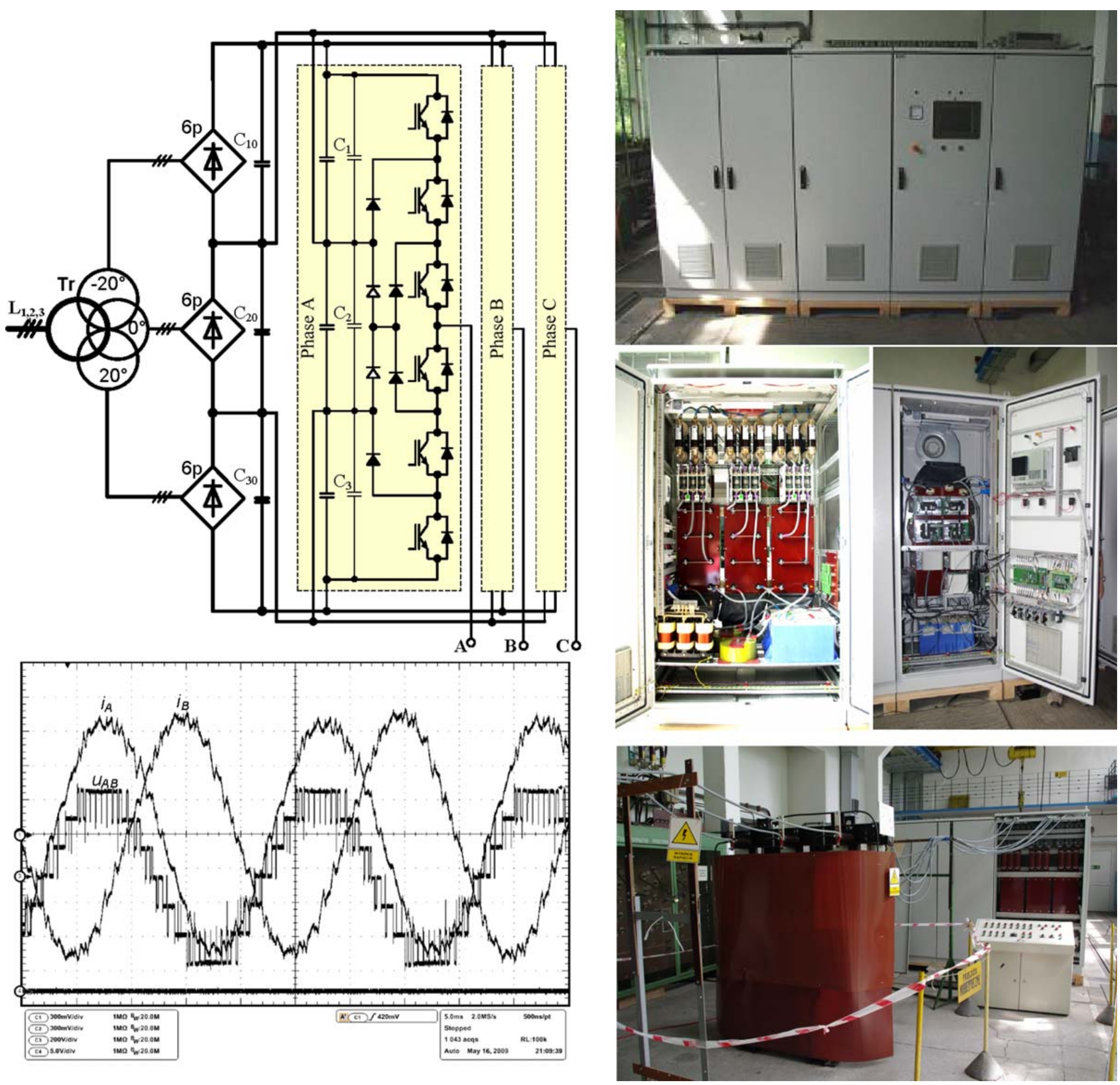

Fig. 21. Scheme and constructional view and voltage and current flows at the output of a prototype 4-level 6 kV/1.0 MVA inverter.

4.3. High power APF device with an LCL coupling filter

In the APF device, presented in Figs. 24–26, in contrast to the majority of Polish and foreign analog ones, an LCL coupling filter has been used. Thanks to this and the implementation of an innovative control algorithm [66], the quality of compensation is decidedly higher than in other known APF devices. The developed device was installed in one Polish hard-coal mine in a device powering a hoisting machine. The specificity of this application were among others the possibility of avoiding the compensation of the 5th and 7th harmonics made it possible to limit the power of each of 4 APF devices (2×2) to 300 kVA. In the subjective opinion of the authors the researched device can be counted among the best solutions of this type in the world.

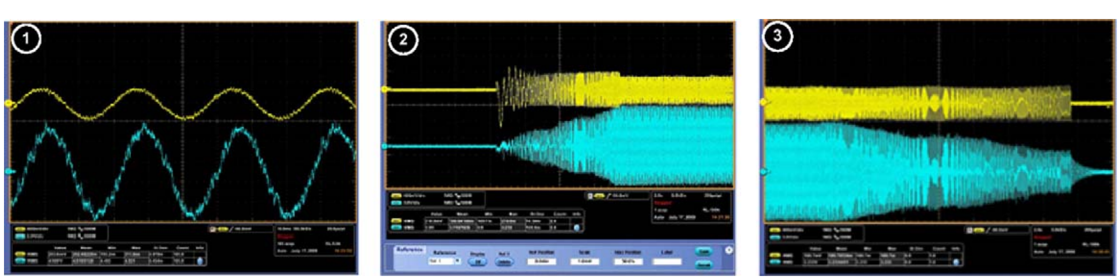

Fig. 22. Current (above) and voltage (below) flows at the terminals of a 6 kV/0.5 kVA motor drive with a load of 200 kW: (1) in steady state, (2) during starting, (3) while braking.

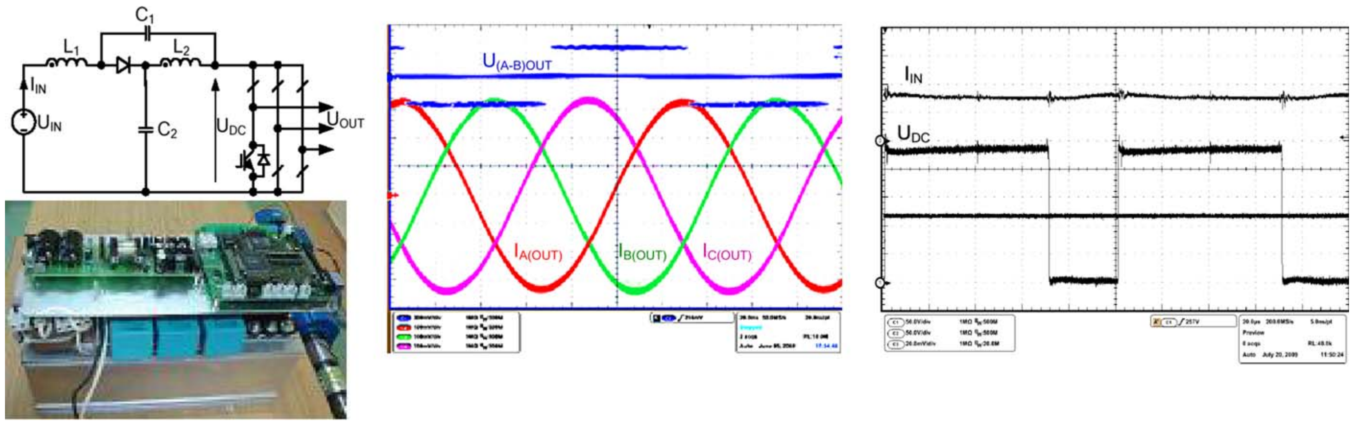

Fig. 23. 3-Phase inverter of the type quasi-Z: scheme, view of laboratory prototype and oscillograms of current and voltage at typical points of the device.

4.4. 18-Pulse rectifier with common mode chokes

Multi-pulse rectifiers with common mode (CM) chokes are an interesting alternative to transformer devices in respect of capacitive filters, if galvanic separation is not required and voltage levels are matched. Their main advantage is the quite small choke power ratio, a few times smaller than transformers. The 18-pulse prototype rectifier with a power of 40 kW with an S-APF device is shown in Fig. 27. This additional small device, with a power ratio equal to 8–10% of the load power, significantly improves the quality of the input current, in particular in the case of distortion and asymmetry of the supply voltage. Moreover, the S-APF device enables the stabilization of DC voltage as well as eliminating (necessary in other cases) large network chokes. This is confirmed by oscillograms presented in Fig. 28. The researched rectifier is designated for use in a distributed EPN as a one-way AC–DC coupler.

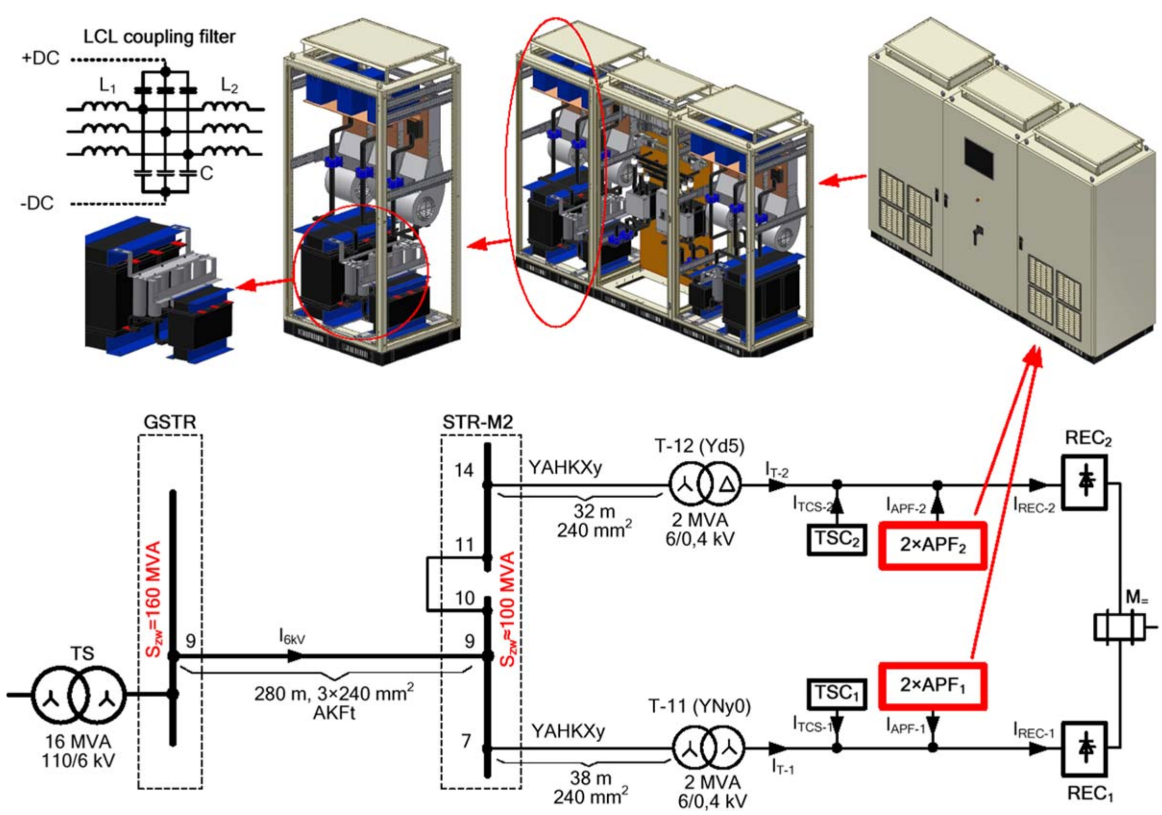

Fig. 24. Construction and scheme of active filter connections in a power supply unit of one hoisting machine at a hard-coal mine.

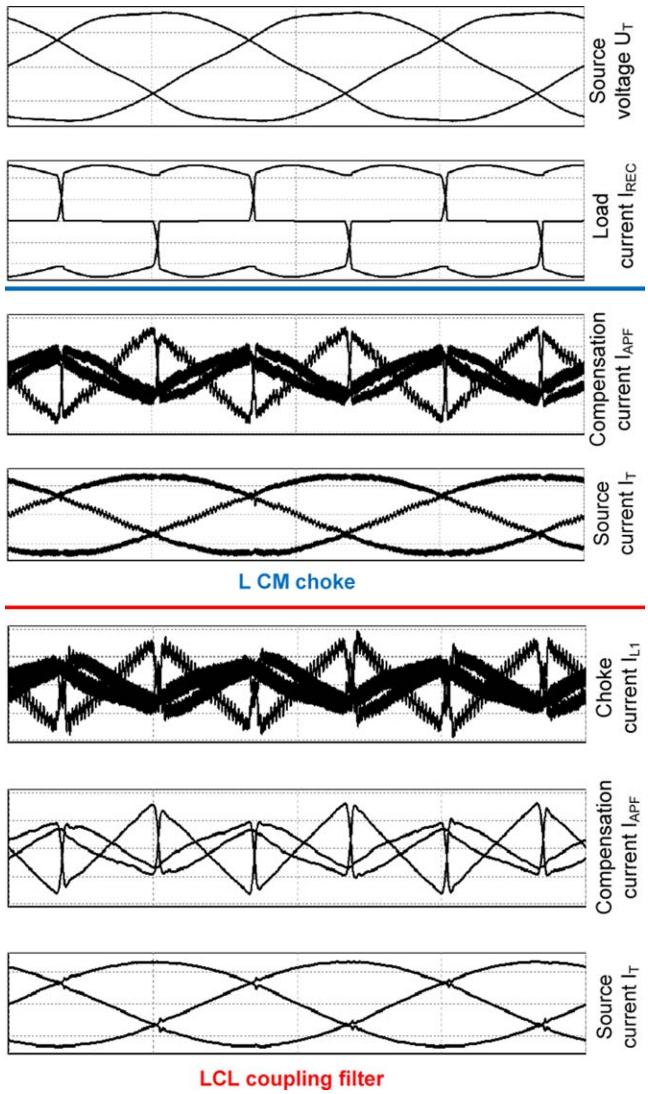

Fig. 25. Results of comparative simulation research on APF devices with L CM choke and LCL coupling filter.

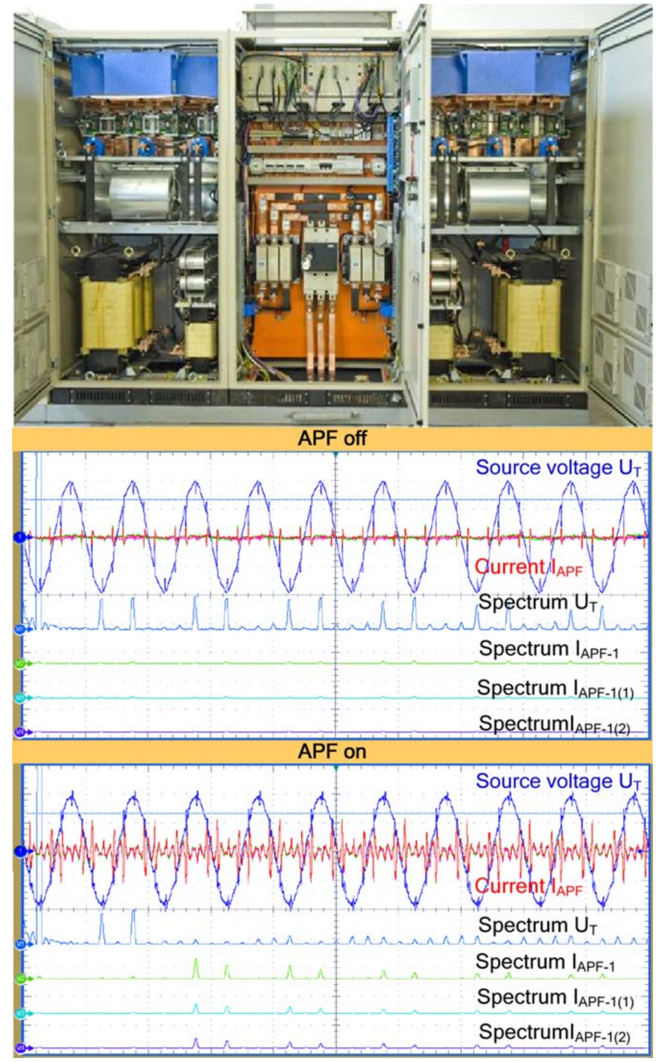

Fig. 26. Constructional view of active filter with LCL coupling filter and results of on-going experimental research in a coalmine hoisting machine power supply device.

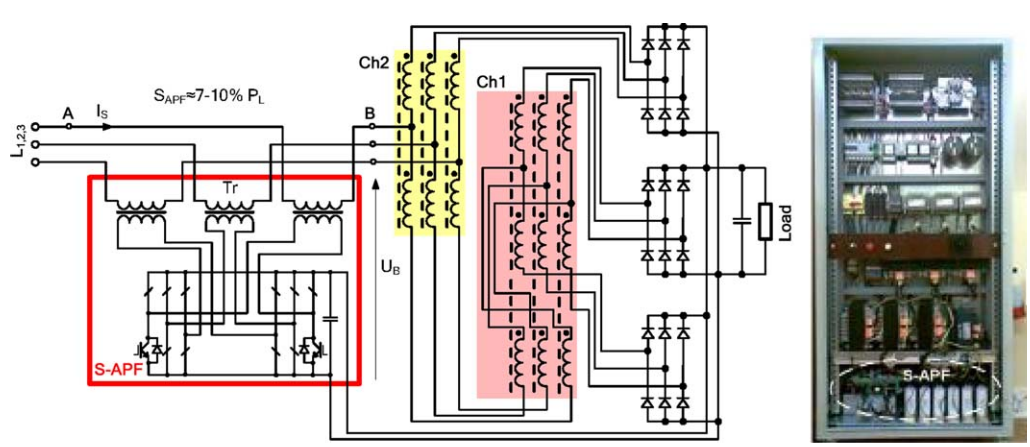

Fig. 27. Scheme and construction of an 18-pulse rectifier with CM chokes and additional S-APF device.

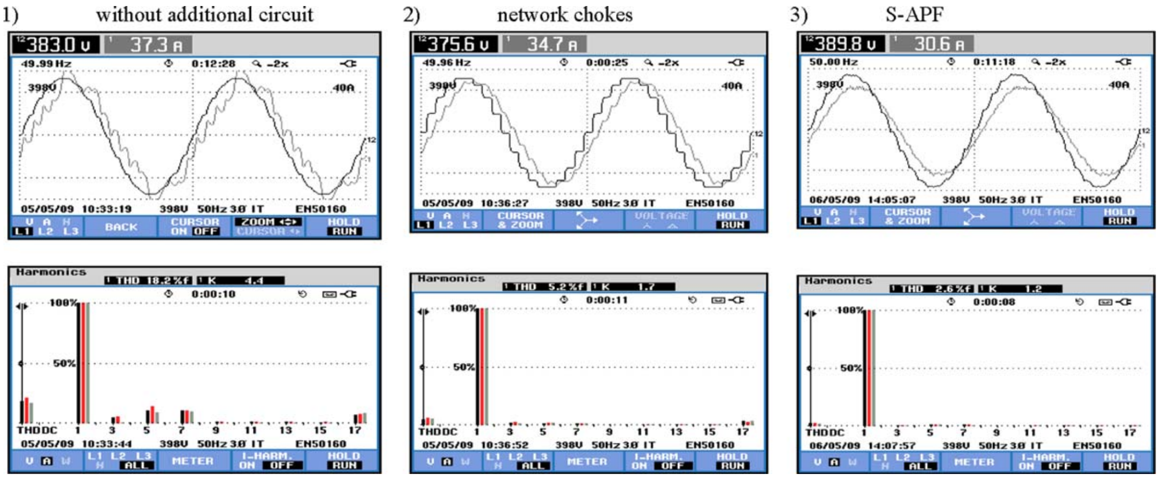

Fig. 28. Voltage waveforms U_B at the input clamps of the choke Ch1, and the network current waveforms and spectrum I_S in relation to the switching circuit between nodes A–B.

5. Conclusions

Power-electronic technology enables a fuller exploitation of existing distributional and transmission resources in the Polish EPN, maintaining and even improving the hitherto state of the power supply security and quality of EE. Of vital significance in this is the effectiveness and response speed of modern PI, permitting smooth and dynamic regulation of lagging parameters due to load changes and power network configurations. Equally important is the fact that such PI can usually fulfill many different functions connected with conditioning of the EE. This all means that power-electronic technology oriented towards EPN leads significantly over traditional technologies, supported by passive LC elements and mechanical switch-coupling devices.

The material presented in no way exhausts the very extensive application possibilities for PI in a EPN. Conscious of the limited length, theoretical discussion has been completely omitted, in particularly concerning the control of PI, but also with respect to many important solutions and conceptions of devices and systems. For the majority of such discussions familiarity with the cited literature will suffice. Nevertheless, the authors hope that this article will inspire the search for new effective solutions within the area discussed, original in their conception and economically far-reaching. This has particular significance in relation to European Union directives in the matter of efficient use of energy [67], finding equal expression in the preparation of the Polish bill on energy efficiency [68], in which, as a national aim (section 2 of the bill) the following is determined: (a) to increase economies of energy through end-users, (b) to increase the effectiveness of energy generation, (c) to reduce the loss of electrical energy in transmission and distribution. It should be pointed out here, that the state policy in the area of transformation of the Polish power industry does not end only with the continuation of the scenario of centralized development of sources of electrical energy, but equally with perspectives of significant development of distributed sources, including renewables [69]. In this context it can be expected that together with the development of small local power industries and the fulfillment of distributed power supply concepts, power-electronic devices fulfilling various functions will constitute standard equipment in modern power sub-stations.

References

[1] Massoud S, Wollenberg B. Toward a smart grid: power delivery for the 21st century. IEEE Power Energy Mag 2005;3(5):34–41.
[2] Strzelecki R, Benysek G. Power electronics in smart electrical energy networks. London: Springer; 2008.
[3] Song YH, Johns AT. Flexible AC transmission systems (FACTS). IEE Power Energy Ser 1999;30.
[4] Machowski J. Elastyczne systemy przesyłowe – FACTS. Przegląd Elektrotechniczny 2002;78(7):189–96.
[5] Sood VK. HVDC and FACTS controllers: applications of static converters in power systems. London: Springer; 2004.
[6] Ghosh A, Ledwich G. Power quality enhancement using custom power devices. Kluwer Academic Pub; 2002.
[7] Strzelecki R, Benysek G, Noculak A. Wykorzystanie urządzeń energoelektronicznych w systemie elektroenergetycznym. Przegląd Elektrotechniczny 2003;79(2):41–9.
[8] Strzelecki R, Supronowicz H. Współczynnik mocy w systemach zasilania prądu przemiennego i metody jego poprawy. Warszawa: Oficyna Wyd. Pol. Warszawskiej; 2000.
[9] Moreno-Muñoz A. Power quality: mitigation technologies in a distributed environment. London: Springer; 2007.
[10] Lubośny Z. Elektrownie wiatrowe w systemie elektroenergetycznym. Warszawa: Wyd. Naukowo-Techniczne; 2006.
[11] Blaabjerg F, Chen Z. Power electronics for modern wind turbines. Morgan & Claypool; 2006.
[12] Heier S, Waddington R. Grid integration of wind energy conversion systems. Wiley Blackwellm; 2006.
[13] Simões MG. Renewable energy systems. Design and analysis with induction generators. CRC Press; 2004.
[14] Boldea I. Variable speed generators. Taylor & Francis Group; 2006.
[15] Gientkowski Z. Autonomiczne prądnice indukcyjne o wzbudzeniu kondensatorowym i przekształtnikowym. Bydgoszcz: Wydawnictwa Uczelniane ATR w Bydgoszczy; 1997.
[16] Bose BK. Power electronics and motor drives: advances and trends. Academic Press; 2006.
[17] Quang NP. Vector control of three-phase AC machines: system development in the practice. Springer; 2008.
[18] Kazimierkowski M, Krishnan R, Blaabjerg F. Control in power electronics. Academic Press; 2002.
[19] Emadi A, Nasiri A, Bekiarov SB. Uninterruptible power supplies and active filters. CRC Press; 2005.
[20] Guerrero MA, Supercapacitors:. Alternative energy storage systems. Przegląd Elektrotechniczny 2009;85(10):188–95.
[21] Sourkounis C, Ni B, Richter F. Comparison of energy storage management methods to smooth power fluctuations of wind parks. Przegląd Elektrotechniczny 2009;85(10):196–200.
[22] Blaabjerg F, Chen Z, Kjaer SB. Power electronics as efficiency interface in dispersed power generation systems. IEEE Trans Power Electron 2004;19(5):1184–94.
[23] Dunlop JP. Photovoltaic systems. American Technical Publication; 2009.
[24] Enjeti P, Palma L, Todorocic MH. Power conditioning systems for fuel cell applications. John Wiley & Sons; 2009.
[25] Lai JS. Power conditioning circuit topologies. IEEE Ind Electron Mag 2009;3(2):24–34.
[26] Luo FL. Essential DC/DC converters. CRC Press; 2006.
[27] Calais M, Myrzik J, Spooner T, Agelidis VG. Inverters for single-phase grid connected photovoltaic systems – an overview. Conf Proc PESC 2002;4(23–27):1995–2000.
[28] Huang Y, Shen M, Peng FZ, Wang J. Z-Source inverter for residential photovoltaic systems. IEEE Trans Power Electron 2006;21(6):176–82.
[29] Strzelecki R, Bury W, Adamowicz M, Strzelecka N. New alternative passive networks to improve the range output voltage regulation of the PWM inverters. Conf Proc APEC 2009;857–63.
[30] Januszewski S, Świątek H, Zymmer K. Przyrządy energoelektroniczne i ich zastosowania. Warszawa: Wyd. Książkowe Instytutu Elektrotechniki; 2008.

[31] Kazimierczuk MK. High frequency magnetics components. John Wiley & Sons; 2009.
[32] Emadi A. Integrated power electronic converters and digital control. CRC Press; 2009.
[33] Liu W, Dirker J, van Wyk JD. Power density improvement in integrated electromagnetic passive modules with embedded heat extractors. IEEE Trans Power Electron 2008;23(6):3142–50.
[34] Ito Y, Zhongqing Y, Akagi H. DC microgrid based distribution power generation system. Conf Proc IPEMC 2004;3:1740–5.
[35] Lasseter R, Paigi P. Microgrid: a conceptual solution. Conf Proc PESC 2004;6:4285–90.
[36] Ise T. Advantages and circuit configuration of a DC Microgrid. In: Proc. of the symposium on microgrids; 2006.
[37] Kakigano H.In: Fundamental characteristics of DC micro-grid for residential houses with cogeneration system in each house; 2008.p. 1–8.
[38] Kawamura A, Pavlovsky M, Tsuruta Y. State-of-the-art. High power density and high efficiency DC–DC chopper circuits fot HEV and FCEV applications. Przegląd Elektrotechniczny 2008;84(9):1–13.
[39] Carlsson A. The back to back converter–control and design. Lund Institute of Technology; 1998.
[40] Strzelecki R, Benysek G, Dębicki H. Uniwersalny wielofunkcyjny sprzęg międzysystemowy. Przegląd Elektrotechniczny 2004;80(3):226–32.
[41] Piróg S. Energoelektronika: układy o komutacji sieciowej i o komutacji twardej. Kraków: Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH; 2006.
[42] Rashid MH. Power electronics handbook. Academic Press; 2006.
[43] Benysek G. Improvement in the quality of delivery of electrical energy using PE systems. London: Springer; 2007.
[44] Han BM, Baek ST, Bae BY, Choi JY. Back to back HVDC system using a 36-step voltage source converter. IEE Proc Generation Transm Distrib 2006;153(6):677–83.
[45] Flourentzou N, Agelidis VG, Demetriades GD. VSC based HVDC power transmission systems: an overview. IEEE Trans Power Electron 2009;24(3):592–602.
[46] Hagiwara M, Fujita H, Akagi H. Performance of a self-commutated BTB HVDC link system under a single-line to ground fault condition. IEEE Trans Power Electron 2003;18(1):278–85.
[47] Rodriguez J, Lai JS, Peng FZ. Multilevel inverters: a survey of topologies, controls, and applications. IEEE Trans Ind Electron 2002;49(4):724–38.
[48] Wu B. High-power converters and AC drives. John Wiley & Sons; 2006.
[49] Hagiwara M, Wada K, Fujita H, Akagi H. Dynamic behavior of a 21 level BTB based power flow controller under single-line-to-ground fault conditions. IEEE Trans Ind Appl 2007;43(5):1379–87.
[50] Inoue S, Akagi H. A bi-directional isolated DC–DC converter as a core circuit of the next-generation medium-voltage power conversion system 2006. Conf Proc PESC 2006;48:314–20.
[51] Wang J, Huang AQ, Sung W, Liu Y, Baliga BJ. Smart grid technologies. IEEE Ind Electron Mag 2009;3(2):16–23.
[52] Jiang Z, Yu H. Hybrid DC and AC linked microgrids: towards integration of distributed energy resources. In: IEEE energy 2030 conf. 2008. p. 1–8.
[53] Strzelecki R, Supronowicz H. Filtracja harmonicznych w sieciach zasilających prądu przemiennego. Wydawnictwo Adam Marszałek; 1999.
[54] Akagi H, Watanabe EH, Aredes M. Instantaneous power theory and applications to power conditioning. John Wiley & Sons; 2007.
[55] Fujita H, Akagi H. Unified power quality conditioner: the integration of series and shunt active filter. IEEE Trans Power Electron 1998;13(2):315–22.
[56] Aredes M, Heumann K, Watanabe E. An universal active power line conditioner. IEEE Trans Power Deliv 1998;13(2):1453–60.
[57] Strzelecki R. Właściwości trójfazowego układu UPQC – modelowanie i weryfikacja eksperymentalna. Przegląd Elektrotechniczny 2005;81(11):295–8.
[58] Wang J, Peng FZ. Unified power flow controller using the cascade multilevel inverter. IEEE Trans Power Electron 2004;19(4):1077–84.
[59] Jauch T, Kara A, Rahmani M, Westermann D. Power quality ensured by dynamic voltage correction. ABB Rev 1998.
[60] Huang CJ, Huang SJ, Pai FS. Design of dynamic voltage restorer with disturbance-filtering enhancement. IEEE Trans Power Electron 2003;18(5): 1202–10.
[61] Ghosh A, Jindal AK, Jodhi A. Design of a capacitor supported dynamic voltage restorer (DVR) for unbalanced and distorted loads. IEEE Trans Power Deliv 2004;19(1):405–13.
[62] Strzelecki R, Benysek G, Wojciechowski D. Układy dynamicznego odtwarzania napięcia. Zastosowanie i właściwości. Przegląd Elektrotechniczny 2008;84(2):33–8.
[63] Zymmer K, Zakrzewski Z, Strzelecki R, Szczepankowski P. Czteropoziomowy falownik napięcia 6 kV typu "Diode clamped". Budowa i sterowanie. Przegląd Elektrotechniczny 2008;84(4):4–9.
[64] Anderson J, Peng FZ. Four quasi-Z-source inverters. Conf Proc PESC 2008;2743–9.
[65] Adamowicz M, Strzelecka N. T-source inverter. Przegląd Elektrotechniczny 2009;85(10):233–8.
[66] Wojciechowski D. Novel controller for 3-phase active power filter with LCL coupling circuit. Przegląd Elektrotechniczny 2009;85(10):208–12.
[67] Parlament Europejski Rada Europy. Dyrektywa 2006/32/WE w sprawie efektywności końcowego wykorzystania energii i usług energetycznych; 2006.
[68] Ustawa o efektywności energetycznej. Warszawa; 2009.
[69] Polski Klub Ekologiczny. Potencjał efektywności energetycznej i redukcji emisji w wybranych grupach użytkowania energii. Droga naprzód do realizacji pakietu klimatyczno-energetycznego. Raport Polskiego Klubu Ekologicznego Okręgu Górnośląskiego w Katowicach we współpracy z Fundacja na Rzecz Efektywnego Wykorzystania Energii, Katowice; 2009.